Expert Systems with Applications 38 (2011) 13773–13784

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Weapon System Capability Assessment under uncertainty based on the evidential reasoning approach

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ARTICLE INFO

Keywords:
Weapon System Capability Assessment
Multiple criteria decision making
Belief structure model
Evidential reasoning approach
Main Battle Tank

ABSTRACT

Weapon System Capability Assessment (WSCA) is the initial point of quantification of capabilities in the military capability planning (MCP). WSCA is often a multiple criteria decision making (MCDM) problem with both quantitative and qualitative information under uncertain environment. In this paper, the analysis process and algorithm for WSCA problem is proposed on the basis of belief structure (BS) model and evidential reasoning (ER) approach which were developed to deal with various types of uncertainties such as ignorance and subjectiveness. First of all, the WSCA criteria hierarchy is built by analyzing how the capability is measured. Secondly, a weapon system capability model is formulated using BS. Thirdly, both qualitative and quantitative information involved in capability measure are transformed into BSs by the data transformation algorithm based on rules. Then, the analytical ER approach is used to aggregate the capability measurement information from sub-capability criteria to top-capability criterion, and the assessed weapon systems are ranked and analyzed according to utility intervals. Finally, a case study of real Main Battle Tank capability assessment is explored to show the proposed process for WSCA.

1. Introduction

In defense, capabilities are understood as the power to achieve a particular operational effect. Military capability planning is planning to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice (Davis, 2002). The initial point in capability planning is the quantification of capabilities (Bui et al., 2007). It is called the Military capability assessment, which includes summing the various elements of the capability against the capability goals. The assessment could include evidence from real operations and expert judgment (TTCP, 2004). The problem studied in this paper, the Weapon System Capability Assessment (WSCA) problem, is viewed as the start point of research on military capability quantification.

In the past two decades, some assessment methods have been developed to analyze the weapon system assessment problem, such as Fuzzy Analytic Hierarchy Process (FAHP) (Cheng & Mon, 1994; Cheng, 1997; Gao, Shi, & Zhang, 2008), Linguistic Analytic Hierarchy Process (Cheng, 1999b), Gray Analytic Hierarchy Process (Gao, Wen, & Liu, 2004), Support Vector Machine Methods (Jiang, Wang, & Wei, 2007), Rough Set and Neural Network (Gu & Song, 2006), and TOPSIS (Dağdevirena, Yavuzb, & Kılınçc, 2009; Wang & Chang, 2007). These different methods were used in different weapon system problems. In particular, FAHP was developed to compare the performance of weapon system described with linguistic and fuzzy judgments by Cheng and Mon (1994). It was also used to study a naval tactical missile systems valuation and selection problem by Cheng (1997). Cheng proposed an Analytic Hierarchy Process (AHP) based ranking method using linguistic variable weights and fuzzy numbers to weapon system evaluation problems with linguistic and vague information and multiple decision makers (Cheng, Yang, & Hwang, 1999a; Cheng, 1999b). An improved FAHP was proposed by Gao et al. (2008) to effectiveness evaluation of missile weapon system with expert judgment. The support vector machine method was used by Jiang et al. (2007) to implement the tradeoffs between system performance parameters and cost to effectively control system cost and enhance cost benefit. Gu and Song (2006) presented a new method for assessing the effectiveness of missile weapon system based on rough set and neural network. And an evaluation model based on the AHP and TOPSIS was developed by Dağdevirena et al. (2009) to help the actors in defense industries to select weapon in a fuzzy environment where the vagueness and subjectivity are handled with linguistic values parameterized by triangular fuzzy number.

Moreover, Main Battle Tank (MBT) weapon system performance evaluation is a classic WSCA problem, and some practical studies

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doi:10.1016/j.eswa.2011.04.179

have been done in this area (Edmond, Dumer, Hanratty, Helfman, & Ingham, 1996; Cheng & Lin, 2002; Zhang, Ma, & Xu, 2005; Deng & Shen, 2006; Chang, Liao, & Cheng, 2007). The turbine engine diagnostics was developed by Edmond et al. (1996) to efficiently diagnose and repair the engine and transmission of Abrams MBT. Cheng and Lin (2002) developed a method to aggregate the subjective judgments of experts described by linguistic terms which can be expressed in trapezoidal or triangular fuzzy numbers. They also developed an algorithm to rank aggregated fuzzy numbers for evaluating the best MBT. The MBTs were evaluated by Deng and Shen (2006) using canonical representation of arithmetic operation on fuzzy numbers instead of complicated fuzzy numbers operations. Linguistic MCDM aggregation model with situational ME-LOWA (Maximal Entropy Linguistic Ordered Weighted Averaging) operators was proposed to aggregate the evaluation data with linguistic preferences for evaluating MBTs by Chang et al. (2007).

Although much work has been done for the weapon system assessment problem, the following two practical issues were not fully addressed in literature and deserve more considerations.

(1) Incomplete information exists in WSCA. Due to various reasons, such as novelty and complexity of weapon systems, complete and precise information about the system may not be available and experts may not have enough knowledge to be able to provide judgments with confidence.
(2) The information about the system could be in different forms, such as quantitative information in the forms of numbers, intervals, probability distributions, and qualitative judgments in the forms of linguistic variables or grades. A comprehensive assessment should include all available information and a good method should be able to cope with them in a unified format.

WSCA often needs to be done under uncertain environment involving dealing with information with incompleteness, ignorance, fuzziness, and vagueness. Therefore, it is necessary to develop a novel assessment process and approach to analyze WSCA problems under uncertainty. In this paper a process based on the evidential reasoning (ER) approach is explored for the purpose. The ER approach was developed by Yang and Singh (1994), Yang and Sen (1994), Yang and Xu (2002), Yang, Wang, Xu, and Chin (2006) on the basis of decision theory and the Dempster–Shafer (D–S) theory of evidence and can be used to model various uncertainties.

The rest of the paper is organized as follows. Section 2 gives the basic description and formulation of a WSCA problem. Then, the process to analyze the problem is proposed in Section 3, including information transformation process and assessment aggregation algorithm based on the evidential reasoning approach. In Section 4, the Main Battle Tank capability assessment example with real data is presented using the proposed approach. The paper is concluded and discussed in Section 5.

2. Problem formulation

A weapon system is the basic unit of military operation. Generally speaking, it is difficult to directly judge whether the weapon system is good or not. The reasons are as follows: (1) A weapon system is large, complex, multi-level, multi-factor and multi-hierarchy. It is made up of thousands of components. (2) When a weapon system is evaluated, some factors should be considered at the same time, such as cost, performance, risk, and operation. These factors are often in conflict and non-commensurable. (3) Different types of information need to be considered, such as quantitative data and qualitative judgments from experts. (4) Uncertainty, such as fuzziness, vagueness, incompleteness and ignorance, may exist in data, which make the assessment difficult.

2.1. Capability assessment criteria hierarchy

General capability of a weapon system often consists of some capability factors. Each capability can often be broken into several sub-capabilities (Bui et al., 2007). Therefore, the whole capability of a weapon system can be assessed by a capability hierarchy.

For example, the *general movement* of a battle vehicle is a general concept and difficult to assess directly, and it needs to be decomposed into detailed concepts, such as *power-to-weight ratio, maximum speed*, and *maximum range*. The two-level hierarchy for assessing the *general movement* of a battle vehicle is given in Fig. 1. If the sub-capability can still not be evaluated directly, then it should be decomposed into more detailed elements, which may lead to a multilevel hierarchical assessment framework.

Generally, suppose there is a simple two-level hierarchy of capability criteria with a general capability criterion C at the top level and L capability criteria c_i, $(i = 1,\dots,L)$ at the bottom level. Define capability criterion C as follows: $C = \{c_1, c_2, \dots, c_i, \dots, c_L\}$ with the weights $w = \{w_1, w_2, \dots, w_i, \dots, w_L\}$, where w_i is the weight of the ith capability criterion c_i with $0 \leqslant w_i \leqslant 1$. Weights play an important role in assessment. They may be estimated using existing methods such as simple rating methods or more elaborate methods based on the pair wise comparisons of attributes (Figueira, Greco, & Ehrgott, 2006; Saaty, 1998).

2.2. Capability assessment using belief structures

The assessment of weapon system capabilities often involves dealing with quantitative and qualitative information, which comes from direct measurements, and experiences or judgments of experts. The belief structure (BS) model provides a unified way to model such an assessment problem. The BS is a distribution using belief degrees to represent the performance of an alternative option on a criterion (Yang & Singh, 1994; Yang & Sen, 1994; Yang & Xu, 2002). It has been successfully applied to the areas of Fuzzy MCDM (Yang et al., 2006), Environmental Impact Assessment (Wang, Yang, & Xu, 2006), New Product Development (Chin, Xu, Yang, & Lam, 2008), Quality Function Deployment (Chin, Wang, Yang, & Poon, 2009), etc.

Firstly, suppose N evaluation grades are defined that collectively provide a complete set of standards for assessing a capability criterion, as represented by $H = \{H_1, H_2, \dots, H_n, \dots, H_N\}$, where H_n is the nth evaluation grade. Without loss of generality, it is assumed that H_{n+1} is preferred to H_n.

For example, in WSCA, the general capability for the battle vehicle is classified into several evaluation grades like 'Worst', 'Poor', 'Average', 'Good', 'Excellent'. Thus a set of grades to assess the battle vehicle capability is defined as follows:

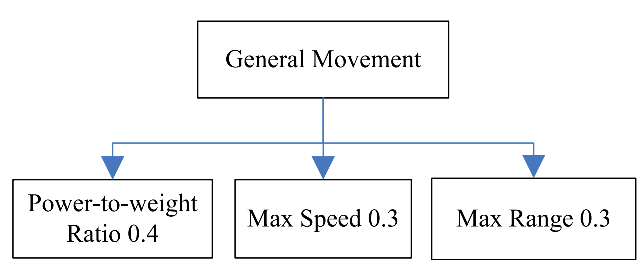

Fig. 1. Assessment criteria hierarchy for general movement.

$$H = \{H_n, n = 1, \ldots, 5\} \\ = \{\text{'Worst'}, \text{'Poor'}, \text{'Average'}, \text{'Good'}, \text{'Excellent'}\}. \quad (1)$$

Then, according to the collected information, the performance of the battle vehicle is compared with the standard of each grade and a belief degree is associated with each grade. For example, to evaluate the *command* & *control* capability of the battle vehicle, an expert may judge that it is mainly (60%) Good with some (30%) Excellent features. Here, 'Good' and 'Excellent' denote distinctive evaluation grades and the percentage values of 60% and 30% are referred to as the belief degrees, which indicates the extents that the corresponding grades are assessed to. The above assessment can be expressed as the following BS: $S(\text{c\&c}) = \{(\text{Good}, 0.5), (\text{Excellent}, 0.3)\}$. Note that this expression describes an incomplete assessment as the sum of the belief degrees is $0.6 + 0.3 < 1$.

Generally, suppose a given assessment of a weapon system against a capability criterion c_i $(i = 1, \ldots, L)$ is mathematically represented as the following distribution:

$$S(c_i) = \{(H_n, \beta_{n,i}), n = 1, \ldots, N\} \quad i = 1, \ldots, L, \quad (2)$$

where $\beta_{n,i} \geqslant 0$, $\sum_{n=1}^{N} \beta_{n,i} \leqslant 1$, and $\beta_{n,i}$ denotes a belief degree. The above distributed assessment reads that the capability c_i is assessed to the grade H_n with the belief degree $\beta_{n,i}$. An assessment $S(c_i)$ is complete if $\sum_{n=1}^{N} \beta_{n,i} = 1$ and incomplete if $\sum_{n=1}^{N} \beta_{n,i} < 1$. A special case is $\sum_{n=1}^{N} \beta_{n,i} = 0$, which denotes a complete lack of information on capability c_i.

Suppose there are M comparable weapon systems ws_m, $(m = 1, \ldots, M)$, a matrix D can be constructed:

$$D = (S(ws_m^i))_{M \times L}, \quad (3)$$

where the element in the mth row and ith column, $S(ws_m^i)$, means the assessment of the mth weapon system ws_m against the ith capability c_i. The matrix D is called belief decision matrix of the capability assessment problem and has $M \times L$ elements. Each element $S(ws_m^i)$ is a capability belief structure as shown in Eq. (2).

The objective of this paper is to model the WSCA problem using capability belief decision matrix D and to assess weapon systems ws_m, $(m = 1, \ldots, M)$ using the information contained in D. The ER approach is proposed for aggregating the information in the belief decision matrix. The following is WSCA analysis process and algorithm.

3. Analysis process and algorithm for WSCA

This section focuses on the process and algorithm for analyzing the WSCA problem. There are two key issues to be discussed: information transformation technique and aggregation algorithm. The aim of the transformation is to prepare the information for the aggregation algorithm. The aggregation is for getting the general assessment result for decision making.

3.1. Information transformation

Various information can be collected in the WSCA problem. For example, the *max speed* of a battle vehicle is measured using the real number, 50 km/h or 70 km/h; and the *command* & *control* is assessed by qualitative linguistic judgment, such as 'Good' or 'Poor'. In order to aggregate these information for WSCA, it is necessary to transform different types of information into the same structure. Such transformation can be conducted using the decision maker's knowledge and experience, based on the *rule based information transformation techniques* developed by Yang (2001).

(1) **Qualitative data transformation:**
In assessment, different words may be used to describe equivalent standards (Yang, 2001). For instance, if a 'very poor' *communication* means that the capability of the *communication* is 'worst' as for as *navigation* is concerned, then an evaluation grade 'very poor' in *navigation* assessment is said to be equivalent to a grade 'worst' in *communication* assessment.
Suppose $H^i = \{H_{n,i}, n = 1, \ldots, N_i\}$ is evaluation grades set for the capability c_i, and $H = \{H_n, n = 1, \ldots, N\}$ is another set of evaluation grades used to evaluate the overall capability of the system. An individual capability assessment using the grade set H^i, $S^i(c_i) = \{(H_{n,i}, \gamma_{n,i}), n = 1, \ldots, N_i\}$, is said to be equivalent to an assessment using the grade set $HS(c_i) = \{(H_n, \beta_{n,i}), n = 1, \ldots, N\}$ if

$$u(H_i) = u(H_{n,i}) \quad \text{and} \quad \beta_{n,i} = \gamma_{n,i}, \quad n = 1, \ldots, N, \quad (4)$$

where $u(H_i)$ and $u(H_{n,i})$ are the utility of grade H_i and $H_{n,i}$ respectively.
Generally, it may not always be the case that $N = N_i$ or $u(H_i) = u(H_{n,i})$. It is also common that $H_{n,i}$ in H^i may not have the same utility as the grade H_n in H. In terms of utility or preferences, if a grade $H_{n,i}$ in H^i means a grade H_l in H to a degree of $\alpha_{l,n}$ $(l = 1, \ldots, N)$ with $0 \leqslant \alpha_{l,n} \leqslant 1$ and $\sum_{l=1}^{N} \alpha_{l,n} = 1$, then we say that

$$H_{n,i} \text{ is equivalent to } \{(H_l, \alpha_{l,n}), l = 1, \ldots, N\}. \quad (5)$$

To implement the transformation process, matrix equations are developed. The above transformation process can be represented by the following matrix equations: (Yang, 2001)

$$\underline{b}_i = \underline{A}_i \times \underline{r}_i \quad (6)$$

with

$$\underline{b}_i = \begin{bmatrix} \beta_{1,i} \\ \beta_{2,i} \\ \vdots \\ \beta_{N,i} \end{bmatrix}, \quad \underline{A}_i = \begin{array}{c|cccc} & H_{1,i} & H_{2,i} & \cdots & H_{N_i,i} \\ H_1 & \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,N_i} \\ H_2 & \alpha_{2,1} & \alpha_{2,2} & \cdots & \alpha_{2,N_i} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ H_N & \alpha_{N,1} & \alpha_{N,2} & \cdots & \alpha_{N,N_i} \end{array}, \quad \underline{r}_i = \begin{bmatrix} \gamma_{1,i} \\ \gamma_{2,i} \\ \vdots \\ \gamma_{N_i,i} \end{bmatrix}, \quad (7)$$

where $\underline{A}_i$ may be referred to as transformation matrix.

(2) **Quantitative data transformation:**
Some capability criteria can be presented by quantitative value. In this case, equivalence rules need to be extracted from decision makers to transform a value to an equivalent assessment using a set of grades so that performance against the quantitative capability criteria can be aggregated in conjunction with other qualitative capability criteria.
To carry out such a transformation, it is fundamental for decision makers to provide basic evaluation rules relating each evaluation grade to a particular value. In general, suppose a value h_n for a capability criterion c is judged to be equivalent to a grade H_n in term of decision makers preferences, i.e. $U(h_n) = U(H_n)$ $(n = 1, \ldots, N)$. Without loss of generality, suppose a larger value h_{n+1} is preferred to a smaller value h_n. Let h_N be the best largest feasible value and h_1 the smallest.
If the capability of an alternative is measured to be the value a on the quantitative criterion c, the transformed equivalent assessment is $S(a) = \{(H_n, \beta_n), n = 1, \ldots, N\}$, according to the single value transformation algorithm proposed by Yang (2001), where

$$\beta_n = \frac{h_{n+1} - a}{h_{n+1} - h_n}, \quad \beta_{n+1} = 1 - \beta_n = \frac{a - h_n}{h_{n+1} - h_n},$$
$$\beta_k = 0, \; k \neq n, n+1. \tag{8}$$

In summary, the above transformation prepares the information for assessment aggregation in the next step.

3.2. Assessment aggregation using the ER approach

Through the data transformation above, all collected qualitative and quantitative information is presented using the same structure, i.e., a belief decision matrix D as shown in Eq. (3). The next step is to aggregate the belief decision matrix to get the assessment of alternative using the ER algorithm and the utility interval ranking method. The ER approach has been developed to evaluates the decision alternative by aggregating the basic attributes, and it has been successfully used for MCDM problem under uncertainty in the past decade (Yang & Singh, 1994; Yang & Sen, 1994; Yang, 2001; Yang & Xu, 2002). ER approach can be directly applied for WSCA by aggregating information in the belief decision matrix D.

Firstly, supposing only one weapon system ws_m is considered here. The belief degrees are transformed into basic probability masses by combining the relative weights and the belief degrees using the following equations:

$$m_{n,i} = m_i(H_n) = w_i\beta_{n,i}, \quad n = 1, \ldots, N; \quad i = 1, \ldots, L, \tag{9}$$

$$m_{H,i} = m_i(H) = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i}, \quad i = 1, \ldots, L, \tag{10}$$

$$\bar{m}_{H,i} = \bar{m}_i(H) = 1 - w_i \quad i = 1, \ldots, L, \tag{11}$$

$$\tilde{m}_{H,i} = \tilde{m}_i(H) = w_i\left(1 - \sum_{n=1}^{N} \beta_{n,i}\right), \quad i = 1, \ldots, L, \tag{12}$$

where there are $m_{H,i} = \bar{m}_{H,i} + \tilde{m}_{H,i}$ and $\sum_{i=1}^{L} w_i = 1$. $m_{n,i}$ denotes the basic probability mass being assessed to the evaluation grade H_n on the capability criterion c_i. $m_{H,i}$ denotes the probability mass assigned to the whole set H, which consists of two parts: $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$, where $\bar{m}_{H,i}$ is caused by the relative importance of capability criteria and $\tilde{m}_{H,i}$ by the incompleteness of the assessment on capability criterion c_i.

Then, the basic probability masses are combined using the following analytical ER algorithm (Wang et al., 2006).

$$\{H_n\} : m_n = k\left[\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i})\right],$$
$$n = 1, \ldots, N, \tag{13}$$

$$\{H\} : \tilde{m}_H = k\left[\prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{L}\bar{m}_{H,i}\right], \tag{14}$$

$$\{H\} : \bar{m}_H = k\left[\prod_{i=1}^{L}\bar{m}_{H,i}\right], \tag{15}$$

$$k = \left[\sum_{n=1}^{N}\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{H,i} + \tilde{m}_{H,i}) - (N-1)\prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i})\right]^{-1}, \tag{16}$$

$$\{H_n\} : \beta_n = \frac{m_n}{1 - \bar{m}_H}, \quad n = 1, \ldots, N, \tag{17}$$

$$\{H\} : \beta_H = \frac{\tilde{m}_H}{1 - \bar{m}_H}, \tag{18}$$

where β_n and β_H represent the belief degrees of the aggregated assessment, to which the general system capability is assessed to the grade H_n and H, respectively. The combined capability assessment can be denoted by

$$S(ws_m) = \{(H_n, \beta_n), n = 1, \ldots, N\}. \tag{19}$$

It has been proved that $\sum_{n=1}^{N}\beta_n + \beta_H = 1$ (Yang & Xu, 2002). Yang and Xu also put forward four axioms and have proved the rationality and validity of the ER algorithm. Note that Eqs. (17) and (18) provide a normalization process to assign the remaining belief $\bar{m}_H$ back to the focal elements proportionally after the combination of all basic criteria, which is necessary as $\bar{m}_H$ is not a degree of ignorance but the unassigned belief caused due to the relative importance of the capability criteria. The analytical ER algorithm clearly shows its nonlinear features and provides a straightforward way to conduct sensitivity analysis for the parameters of the ER approach such as weights and belief degrees. It also facilitates the estimation and optimization of these parameters (Wang et al., 2006).

3.3. Ranking of weapon systems based on utility interval

In order to compare M weapon systems according to combined capability assessment result $S(ws_m)$ described by Eq. (19), maximum, minimum and average utilities are introduced and used to rank them (Yang & Sen, 1994; Yang & Xu, 2002). Suppose the utility of an evaluation grade H_n is $u(H_n)$, then the expected utility of aggregated capability assessment $S(ws_m)$ is defined as follows:

$$u(S(ws_m)) = \sum_{n=1}^{N}\beta_n(ws_m)u(H_n). \tag{20}$$

The belief degree $\beta_n(ws_m)$ stands for the lower bound of likelihood that ws_m is assessed to H_n, whilst the corresponding upper bound of the likelihood is given by $(\beta_n(ws_m) + \beta_H(ws_m))$, which leads to the establishment of a utility interval if the assessment is incomplete. Without loss of generality, suppose the least preferred assessment grade having the lowest utility is H_1 and the most preferred assessment grade having the highest utility is H_N. The maximum, minimum and average utilities of ws_m can be calculated by

$$u_{\max}(ws_m) = \sum_{n=1}^{N-1}\beta_n(ws_m)u(H_n) + (\beta_N(ws_m) + \beta_H(ws_m))u(H_N), \tag{21}$$

$$u_{\min}(ws_m) = (\beta_1(ws_m) + \beta_H(ws_m))u(H_1) + \sum_{n=2}^{N}\beta_n(ws_m)u(H_n), \tag{22}$$

$$u_{avg}(ws_m) = \frac{u_{\max}(ws_m) + u_{\min}(ws_m)}{2}. \tag{23}$$

The final assessment result is represented by the $u_{\max}(ws_m)$, $u_{\min}(ws_m)$ and $u_{avg}(ws_m)$. It is obvious that if $u_{\min}(ws_l) \geqslant u_{\max}(ws_k)$, the weapon system ws_l is said to be preferred to the weapon system ws_k; if $u_{\min}(ws_l) = u_{\min}(ws_k)$ and $u_{\max}(ws_l) = u_{\max}(ws_k)$, the weapon system ws_l is said to be indifferent to the weapon system ws_k. In other cases, average utility may be used to generate an average ranking, but this kind of ranking may be inconclusive and unreliable (Yang & Sen, 1994; Yang & Xu, 2002).

3.4. Proposed analysis process for WSCA

As the result of the above discussion, an analysis process for WSCA can be proposed as follows:

Step 1. According to characteristics of a particular weapon system, the capability criterion is decomposed into several sub-capability criteria and a capability hierarchy is built.

Step 2. Quantitative and qualitative information of weapon systems is collected from actual measurements, specifications, descriptions, or expert experiences, which provide original assessment data sources.

Step 3. All types of collected information, qualitative, quantitative, or linguistic, are transformed into the BS model by the data transformation algorithms, (4)–(7) for qualitative data and (8) for quantitative data.

Step 4. The assessment is aggregated by using the ER algorithm as given in (9)–(18) from the sub-capability criteria to top-capability criteria.

Step 5. Using the utility interval algorithm (20)–(23), the assessment result is calculated and analyzed.

4. Application: Main Battle Tank capability assessment

Main Battle Tank (MBT) is one type of racked, heavily armoured fighting vehicle, which is used for carrying out breakthrough, exploitation, and infantry support in modern battlefield. It usually combines operational mobility and tactical offensive and defensive capabilities. Firepower of a MBT is normally provided by a large-calibre main gun in a rotating turret and secondary machine guns, while heavy armour and all-terrain mobility provide protection for the tank and its crew, allowing it to perform all primary tasks of the armoured troops on the battlefield. MBT is also called as "the backbone of modern ground forces" (Christopher, 2005). In this section, a real MBT assessment example is presented and analyzed by the proposed algorithm and process above.

Step 1. Building the capability assessment criteria hierarchy of MBT:

For MBT capability assessment, there are four top capabilities criteria to be taken into account. They are *attack* capability, *mobility* capability, *defense* capability, and *communication* & *command* (*C*&*C*) capability (Cheng & Lin, 2002; Chang et al., 2007; Deng & Shen, 2006; Zhang et al., 2005). It is too difficult and complex to analyze these top capabilities directly. So it is better to break them down to sub-capabilities for which measurement data can be identified.

(1) **Attack capability:**

Attack is the ability for tanks to engage and destroy a target. It includes two sub-capabilities: armament and ammunition. The main weapon of MBT is a single, large-caliber gun mounted in a fully traversing turret. In addition, tanks carry smaller caliber armament, such as a coaxial gun, a heavier antiaircraft machine gun, and smoke grenade launchers, for short-range defense when engaging infantry, light vehicles or aircraft, where the main gun would be ineffective. Table 1 gives the main description on the sub-capabilities which determine the attack capability of a MBT.

(2) **Mobility capability:**

The mobility of a MBT is described as its battlefield or tactical mobility and its strategic mobility. Tactical mobility can be broken down into agility and obstacle clearance. The former describes the tank's acceleration, braking, speed and rate of turn on various terrain. The latter is the ability to travel over rough terrain and

Table 1
Attack sub-capability description.

		Description
Armament	Main gun	Main gun of a MBT is a specific weapon for the particular needs of the tank. It usually is large-caliber high-velocity gun, which is mounted in the cramped confines of an armored turret. It should be capable of firing kinetic energy penetrations, high explosive anti-tank rounds, and in some cases guided missiles. As the MBT's primary armament, it is almost always employed in a direct-fire mode to defeat a variety of ground targets, including dug-in infantry, lightly-armored vehicles, and especially other heavily-armored tanks
	Coaxial gun	A coaxial gun is a machine gun which is mounted side-by-side with the main gun to fire along a parallel axis. It is usually aimed by the main gun control and used to engage infantry or other targets when the main gun collateral damage would be excessive, or to conserve main gun ammunition
	Anti-aircraft gun	An anti-aircraft gun is a particular armament to engaging hostile military aircraft for serious threat to low-flying attack aircraft or attack helicopters
	Smoke grenade launchers	A grenade launcher is a weapon which launches a grenade with greater distances, more accuracy, and higher velocity than a soldier could throw it by hand. And Smoke grenades are canister-type grenades used as ground-to-ground or ground-to-air signaling devices, target or landing zone marking devices, or screening devices for unit movements
Ammunition		Ammunition of a MBT refers to the supply of bullets to be fired from the guns (main gun, coaxial gun, anti-aircraft gun, grenades launchers). For example, bombs, missiles, warheads, and so on

Table 2
Mobility sub-capability description.

		Description
General movement	Power-to-weight ratio	Power-to-weight ratio is a measurement of actual performance of MBT engine and power sources. Its calculating formula is engine power divided by weight. It gives an idea of the MBT's acceleration
	Max speed	The maximum movement speed MBT can attain
	Max range	The maximum distance MBT can move with full fuel
Over obstacle	Ground clearance	Ground clearance is the amount of space between the base of the MBT's tracks and the underside of the armoured plate; for a MBT, ground clearance presents an additional factor in a vehicle's overall performance: a higher ground clearance means that the vehicle minus the chassis is higher to the ground and thus easier to ride over obstacle
	Fording	Fording is used to describe the capability of MBT for crossing the river or stream. The fording depth for MBTs is limited by the height of the engine air intake and driver's position
	Gradient	This factor describes the degrees MBT can climb gradient
	Side slope	This factor describes the degrees MBT can traverse a side slope
	Vertical obstacle	This factor the height MBT can ride over the vertical obstacle
	Trench	A trench is a type of excavation or depression in the ground. This factor describes the depth of a trench a MBT can pass

vertical obstacles like low walls or trenches or through water. Strategic mobility is the relative ease with which a military asset can be transported between theatres of operation and falls within the scope of military logistics. A MBT is highly mobile and able to travel over most types of terrain due to its continuous tracks and advanced suspension. Table 2 describes the main sub-capabilities which determine the mobility capability of a MBT.

(3) **Defense capability:**

Defense is the tank's ability to resist being detected, and disabled or destroyed by enemy fire. The measure of a MBT's defense is the combination of its ability to avoid detection and being hit by enemy fire, its resistance to the effects of enemy fire, and its capacity to sustain damage whilst still completing its objective or at least protecting its crew. The main sub-capabilities which determine defense capability of a MBT are depicted in Table 3.

(4) **Communication & command capability:**

Communication and command capability includes command, control, communications, intelligence, surveillance and reconnaissance. These functions are performed through various electrical equipment, computers, radars, network, command control systems, information systems, and so on. We analyze C&C through several sub-capabilities as shown in Table 4.

Finally, the capability assessment criteria hierarchy of MBT is built as Fig. 2. The numbers mean the weights of the capability criterion w_i. In the same assessment level and under the same upper level capability, they satisfy $\sum_{i=1}^{L} w_i = 1$.

Step 2. Collecting data and information of MBTs:

We choose four MBTs as assessment entities, which are Type 98 MBT (China), M1A2 Abrams (USA), Challenger 2E MBT (UK), and

Table 3
Defense sub-capability description.

	Description
Armour protection	Thick armour is used to protect effectively the MBT and its crew. It should counter a wide variety of antitank threats
Camouflage & deception	Camouflage and deception are the methods of concealing itself by looking the same as the surroundings or like something else
Concealment	Concealment (hiding) is the capability of obscuring a MBT from view or rendering it inconspicuous

Table 4
Communication & command sub-capability description.

	Description
Command & control	Command and control functions are performed through an arrangement of equipment, communications, facilities, and procedures employed by a MBT commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission
Communication	Communication is a field of military activities, tactics and equipment dealing with communication. It describes ability of connecting MBT with a higher commander or other battle units
Navigation	Navigation is the process of reading, and controlling the movement of MBT from one place to another
Surveillance & reconnaissance	Surveillance & reconnaissance denotes exploration conducted to gain information. It is the active seeking to determine a foe's intentions by collecting and gathering information about an enemy's composition and capabilities along with pertinent environmental conditions

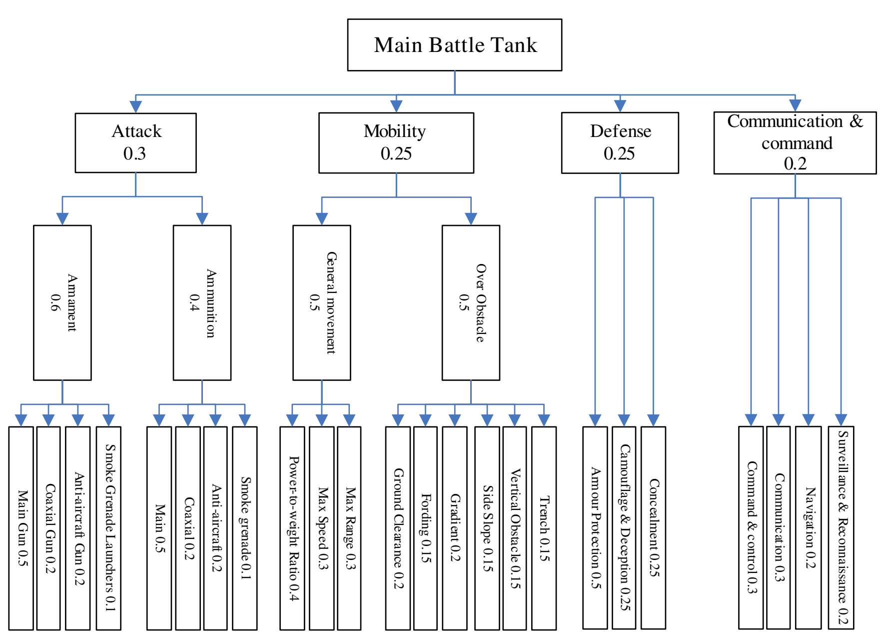

Fig. 2. Assessment framework of MBTs.

Leopard 2 MBT (Germany). The real data comes from the Jane's (Christopher, 2005). Note that quantitative data is obtained by measuring the entities, while the qualitative information is collected from documents and judgment of experts. Some qualitative information is described as follows.

(1) **Type 98 MBT (China):**

The Chinese Type 98 MBT is the most advanced MBT in People's Liberation Army, ant it has better performance than earlier MBTs in defense protection and communication & command.

In the aspect of defense protection, the hull of the Type 98 which is of all-welded steel armour and the explosive reactive armour over the frontal arc provide a higher level of protection in battlefield. The armour package on the front allows the armour to be rapidly changed if it is hit. In addition, the pole-type laser detector, the infra-red jammer, and the laser dazzler device enhance survivability by making the threat vehicle blind when in battle.

Standard equipment of Type 98 for communication & command capability include an NBC system, fire detection and suppression system, and global positioning system. In its immediate front, there are three periscopes and one passive periscope for driving at night, which is understood to be of the image intensification type and has an effective range of 200 m. To the immediate front of the commander's position is a stabilized 360° day/night panoramic sight that also includes a laser range-finder. The latter feeds information to the computer enabling the 125 mm weapon to be rapidly laid onto the target while the Type 98 is stationary or moving.

(2) **M1A2 Abrams (USA):**

The M1A2 MBT provides enhanced communication and command capability over M1A1 MBT. The improvements of the M1A2 include Improved Commander's Weapon Station (ICWS), Commander's Independent Thermal Viewer (CITV), an Inter-Vehicular Information System (IVIS), Position/Navigation System (POS/NAV) and several survivability initiatives.

The fire-control system includes the laser range-finder, full-solution solidstate digital computer and stabilized day/thermal night sight. Centre day periscope, the image intensification periscope and night driving periscope are provided to driver and commander for all-day-time surveillance. In addition, it also has the infra-red Thermal Imaging System (TIS), the digital fire-control computer, and the General Dynamics Land Systems Inter-Vehicular Information System (IVIS). By IVIS, five M1A2 MBTs, one Bradley Fighting Vehicle and one OH-58D helicopter were able to maintain constant digital communication between each other and a base communication system.

(3) **Challenger 2E MBT (UK):**

Challenger 2E MBT is a further development of the Challenger 2 with a number of enhanced capabilities in the key areas of mobility, situation awareness, target acquisition and survivability.

The hull and turret of Challenger 2E have been designed to minimize millimetric radar returns, to avoid detection and lock-on by guided missiles. And Survivability is further enhanced to avoid detection by reducing the overall signature and using new advanced armour technology which incorporates new materials for improved protection against both chemical energy and kinetic energy attack.

As to communication & command capability, a good suite of day/thermal night observation and gunnery equipment, has greatly enhanced target acquisition capabilities. It has common 2nd generation thermal imaging systems and allow either the commander or gunner to detect and engage targets under almost all weather conditions at long range with greater accuracy. With enhanced versions of fire-control system and Battle Management System, Challenger 2E provides the commander, gunner and driver with enhances battlefield awareness, such as own vehicle position, friendly and enemy force location, automatic fire/explosion detection, etc.

(4) **Leopard 2 MBT (Germany):**

Standard equipment on the Leopard 2 includes a collective NBC system, power pack preheating, crew compartment heater, a fire extinguishing system, electric bilge pumps and an escape hatch in the hull floor behind the driver.

Table 5
The collected information of four MBTs.

	Type 98 MBT (China)	M1A2 Abrams (USA)	Challenger 2E MBT (UK)	Leopard 2 MBT (Germany)
Main gun	1 × 125 mm smoothbore gun	1 × 120 mm smoothbore gun	1 × 120 mm rifled tank gun	1 × 120 mm smoothbore gun
Coaxial gun	1 × 7.62 mm MG	1 × 7.62 mm MG	1 × 7.62 mm MG	1 × 7.62 mm MG
Anti-aircraft gun	1 × 12 mm MG	1 × 12.7 mm MG 1 × 7.62 mm MG	1 × 7.62 mm or 12.7 mm MG	1 × 7.62 mm MG
Smoke grenade launchers	2 × 6	2 × 6	2 × 5	N/A
Ammunition	42	40	40	42
	2000	12,400	4000	4750
	300	1000	N/A	N/A
	20	24	N/A	N/A
Power-to-weight ratio	24 hp/t	23.77 hp/t	24 hp/t	27 hp/h
Max speed	65 km/h	67.6 km/h	65 km/h	72 km/h
Max range	650 km	426 km	550 km	550 km
Ground clearance	0.47 m	0.48 m	0.50 m	0.53 m
Fording	2.5 m	1.98 m	2 m	1 m
Gradient	60%	60%	60%	60%
Side slope	40%	40%	30%	30%
Vertical obstacle	0.85 m	1.067 m	1 m	1.1 m
Trench	3 m	2.743 m	2.5 m	3 m
Armour protection	B	A	A	B
Camouflage & deception	A−	B+	B+	B+
Concealment	B+	B+	A	B+
Command & control	B	A−	A−	B+
Communication	B	A	N/A	B
Navigation	B−	B+	B+	N/A
Surveillance & reconnaissance	B+	B+	B+	B

The hull of the Leopard 2 has a spaced multilayer armour. Improved armour protection over the frontal arc, the side skirts, and under the existing floor provides a significant increase in protection against both kinetic and chemical energy attack.

In aspect of communication & command capability, the Leopard 2 provides the three day observation periscopes, the centre one of that can be replaced by a passive night periscope for the driver; periscopes for all-round observation for commander; and integrated laser range-finder, roof-mounted observation periscope, and thermal image unit which are linked to the fire-control computer for the gunner. Furthermore the commander can control all functions of the fire-control system and the weapon slave system by a computer-controlled testing board. In addition, the fire-control computer successively calculates the angle of sight and lateral angular lead for the main armament.

According to the description above, without loss of generality, seven grades {C, C+, B−, B, B+, A−, A} are used to measure the extent which qualitative criteria are evaluated. From C to A, it denotes the better and better capability. All information is collected in Table 5, including quantitative and qualitative capability criteria information.

Step 3. Building evaluation grades and transforming original information:

The capability of a MBT can be evaluated to five grades 'Worst', 'Poor', 'Average', 'Good', and 'Excellent', which can be formulated as Eq. (1).

$$
\begin{aligned}
H &= \{H_j, j = 1, \ldots, 5\} \\
&= \{\text{'Worst'(W)}, \text{'Poor'(P)}, \text{'Average'(A)}, \text{'Good'(G)}, \text{'Excellent'(E)}\}.
\end{aligned}
$$

Table 6
The rules of quantitative capability criteria.

$H_{n,i}$	"Worst"	"Poor"	"Average"	"Good"	"Excellent"
Main gun (mm)	110	115	120	125	130
Coaxial gun (mm)	7	8	10	12	14
Anti-aircraft gun (mm)	7	8	10	12	14
Smoke grenade launchers (2 * x)	3	4	5	6	7
Ammunition (main)	36	38	40	42	44
Ammunition (coaxial)	2000	4000	7000	10,000	13,000
Ammunition (anti-aircraft)	200	500	900	1300	1500
Ammunition (smoke grenade)	20	22	24	26	28
Power-to-weight ratio (hp/t)	22	23	24	26	28
Max speed (km/h)	45	55	65	75	85
Max range (km)	300	400	500	600	700
Ground clearance (m)	0.30	0.40	0.50	0.60	0.70
Fording (m)	1	1.4	1.7	2	2.5
Gradient	45%	50%	55%	60%	65%
Side slope	20%	25%	30%	40%	50%
Vertical obstacle (m)	0.5	0.8	1	1.2	1.5
Trench (m)	1.5	2	2.5	3	3.5

Table 7
The rules of qualitative capability criteria.

	"Worst"	"Poor"	"Average"	"Good"	"Excellent"
C	1	0	0	0	0
C+	0.6	0.4	0	0	0
B−	0	0.6	0.4	0	0
B	0	0	1	0	0
B+	0	0	0.4	0.6	0
A−	0	0	0	0.4	0.6
A	0	0	0	0	1

Table 8
The belief decision matrix of MBTs.

Capability (weight)			Type 98 MBT (China)	M1A2 Abrams (USA)	Challenger 2E MBT (UK)	Leopard 2 MBT (Germany)
Attack (0.3)	Armament (0.6)	Main gun (0.5)	{(G,1.0)}	{(A,1.0)}	{(A,1.0)}	{(A,1.0)}
		Coaxial gun (0.2)	{(W,0.38),(P,0.62)}	{(W,0.38),(P,0.62)}	{(W,0.38),(P,0.62)}	{(W,0.38),(P,0.62)}
		Anti-aircraft gun (0.2)	{(G,1.0)}	{(G,0.65),(E,0.35)}	{(G,0.65),(E,0.35)}	{(W,0.38),(P,0.62)}
		Smoke grenade launchers (0.1)	{(G,1.0)}	{(G,1.0)}	{(A,1.0)}	{(A,0.0)}
	Ammunition (0.4)	Main (0.5)	{(G,1.0)}	{(A,1.0)}	{(A,1.0)}	{(G,1.0)}
		Coaxial (0.2)	{(W,1.0)}	{(G,0.2),(E,0.8)}	{(P,1.0)}	{(P,0.75),(A,0.25)}
		Anti-aircraft (0.2)	{(W,0.67),(P,0.33)}	{(A,0.75),(G,0.25)}	{(A,0.0)}	{(A,0.0)}
		Smoke grenade (0.1)	{(W,1.0)}	{(A,1.0)}	{(A,0.0)}	{(A,0.0)}
Mobility (0.25)	General movement (0.5)	Power-to-weight ratio (0.4)	{(A,1.0)}	{(P,0.23),(A,0.77)}	{(A,1.0)}	{(G,0.5), (E,0.5)}
		Max speed (0.3)	{(A,1.0)}	{(A,0.74),(G,0.26)}	{(A,1.0)}	{(A,0.3),(G,0.7)}
		Max range (0.3)	{(G,0.5),(E,0.5)}	{(P,0.74),(A,0.26)}	{(A,0.5),(G,0.5)}	{(A,0.5),(G,0.5)}
	Over obstacle (0.5)	Ground clearance (0.2)	{(P,0.3),(A,0.7)}	{(P,0.2),(A,0.8)}	{(A,1.0)}	{(A,0.7),(G,0.3)}
		Fording (0.15)	{(E,1.0)}	{(A,0.07),(G,0.93)}	{(G,1.0)}	{(W,1.0)}
		Gradient (0.5)	{(G,1.0)}	{(G,1.0)}	{(G,1.0)}	{(G,1.0)}
		Side slope (0.15)	{(G,1.0)}	{(G,1.0)}	{(A,1.0)}	{(A,1.0)}
		Vertical obstacle (0.15)	{(P,0.75),(A,0.25)}	{(A,0.67),(G,0.33)}	{(A,1.0)}	{(A,0.5),(G,0.5)}
		Trench (0.15)	{(G,1.0)}	{(A,0.51),(G,0.49)}	{(A,1.0)}	{(G,1.0)}
Defense (0.25)	Armour Protection (0.5)		{(A,1.0)}	{(E,1.0)}	{(E,1.0)}	{(A,1.0)}
	Camouflage & deception (0.25)		{(G,0.4), (E,0.6)}	{(A,0.4),(G,0.6)}	{(A,0.4),(G,0.6)}	{(A,0.4), (G,0.6)}
	Concealment (0.25)		{(A,0.4),(G,0.6)}	{(A,0.4),(G,0.6)}	{(E,1.0)}	{(A,0.4),(G,0.6)}
Communication & command (0.2)	Command & control (0.3)		{(A,1.0)}	{(G,0.4),(E,0.6)}	{(G,0.4), (E,0.6)}	{(A,0.4),(G,0.6)}
	Communication (0.3)		{(A,1.0)}	{(E,1.0)}	{(A,0.0)}	{(A,1.0)}
	Navigation (0.2)		{(P,0.6),(A,0.4)}	{(A,0.4),(G,0.6)}	{(A,0.4),(G,0.6)}	{(A,0.0)}
	Surveillance & reconnaissance (0.2)		{(A,0.4), (G,0.6)}	{(A,0.4),(G,0.6)}	{(A,0.4),(G,0.6)}	{(A,1.0)}

Table 9
The assessment aggregation results.

	Type 98 MBT (China)	M1A2 Abrams (USA)	Challenger 2E MBT (UK)	Leopard 2 MBT (Germany)
Attack	0.1225, 0.0554, 0.0000, 0.8221, 0.0000, 0.0000	0.0324, 0.0529, 0.7394, 0.1181, 0.0572, 0.0000	0.0328, 0.0973, 0.7404, 0.0562, 0.0302, 0.0431	0.0837, 0.1871,0.4431, 0.1942, 0.0000, 0.0919
Mobility	0.0000, 0.0000, 0.7632, 0.1184, 0.1184, 0.0000	0.0000, 0.2812, 0.6584, 0.0604, 0.0000, 0.0000	0.0000, 0.0000, 0.8982, 0.1018, 0.0000, 0.0000	0.0000, 0.0000, 0.2048, 0.6109, 0.1843, 0.0000
Defense	0.0000, 0.1609, 0.1679, 0.5405, 0.1307, 0.0000	0.0000, 0.0000, 0.1649, 0.2552, 0.5799, 0.0000	0.0000, 0.0000, 0.0667, 0.1000, 0.8333, 0.0000	0.1259, 0.0000, 0.3599, 0.5141, 0.0000, 0.0000
Communication & command	0.0000, 0.0848, 0.8304, 0.0848, 0.0000, 0.0000	0.0000, 0.0000, 0.1350, 0.3532, 0.5118, 0.0000	0.0000, 0.0000, 0.1595, 0.4172, 0.1953, 0.2279	0.0000, 0.0000, 0.7049, 0.1660, 0.0000, 0.1291

Table 10
The final assessment result.

Type 98 MBT (China)	M1A2 Abrams (USA)	Challenger 2E MBT (UK)	Leopard 2 MBT (Germany)
0.0343, 0.0662, 0.3913, 0.4529, 0.0553, 0.0000	0.0091, 0.0776, 0.4916, 0.1738, 0.2480, 0.0000	0.0093, 0.0275, 0.5425, 0.1354, 0.2376, 0.0477	0.0511, 0.0506, 0.4305, 0.3829, 0.0403, 0.0446

All sub-capability criteria may then be assessed with reference to this set of evaluation grades using information transformation algorithm.

From Table 5, twenty-one capabilities criteria are taken into account. Among these, there are fourteen quantitative and seven qualitative capabilities. For example, *power-to-weight ratio* (*PW*) is a quantitative capability criterion. To assess it, assuming equivalence rules have been acquired as follows:

1. If the *PW* of the MBT is 22 hp/t, then its *PW* capability is Worst ($h_1 = 22$);
2. If the *PW* of the MBT is 23 hp/t, then its *PW* capability is Poor ($h_2 = 23$);
3. If the *PW* of the MBT is 24 hp/t, then its *PW* capability is Average ($h_3 = 24$);
4. If the *PW* of the MBT is 26 hp/t, then its *PW* capability is Good ($h_4 = 26$);
5. If the *PW* of the MBT is 28 hp/t, then its *PW* capability is Excellent ($h_5 = 28$);

Based on the rules above, a set of evaluation grades for *PW* capability equivalent to *H* is: $H^{PW} = \{h_1, h_2, h_3, h_4, h_5\} = \{22, 23, 24, 26, 28\}$.

From Table 5, *PW* capability of Leopard 2 MBT is measured by 27 hp/t. It means that it should be evaluated to grades H_4 and H_5 with the belief degrees $\{\beta_4, \beta_5\}$, which can be calculated by Eq. (8), $\beta_4 = 0.500$, $\beta_5 = 0.500$. So, the *Power-to-weight ratio* capability of Leopard 2 MBT assessed using the general evaluation grades *H* is $S^{PW}(Leppard2MBT) = \{(H_4, 0.5000), (H_5, 0.5000)\}$.

For a qualitative capability criterion, we take *Camouflage & deception (C& D)* for example. Assume that individual evaluation grades $H^{C\&D}$ for *C& D* is {C, C+, B−, B, B+, A−, A}, while the general evaluation grade *H* is {'Worst', 'Poor', 'Average', 'Good', 'Excellent'}. Suppose the transformation matrix is given by experts as follows:

$$\underline{A}_i = \begin{array}{r} \\ \text{Worst} \\ \text{Poor} \\ \text{Average} \\ \text{Good} \\ \text{Excellent} \end{array} \begin{array}{c} \begin{array}{ccccccc} C & C+ & B- & B & B+ & A- & A \end{array} \\ \begin{bmatrix} 1 & 0.6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.4 & 0.6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.4 & 1 & 0.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.6 & 0.4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.6 & 1 \end{bmatrix} \end{array}.$$

From Table 5, the *C&D* capability of Type 98 MBT is evaluated to 'A−', i.e. $S^{C\&D} = \{(H_{n,i}, \gamma_{n,i})\} = \{(\text{'A−'}, 1)\}$ Using the transformation matrix $\underline{A}_i$ and Eqs. (5)–(7), we can obtain $\beta_i = \underline{A}_i \times \underline{r}_i = (0, 0, 0, 0.4, 0.6)$. That is the *C&D* capability of Type 98 MBT is assessed as $S(C\&D) = \{(H_4, \beta_4), \ (H_5, \beta_5)\} = \{(\text{Good}, 0.4), (\text{Excellent}, 0.6)\}$.

Tables 6 and 7 give all rules of transforming the original assessments to the assessments expressed by the general grades *H* on all other quantitative and qualitative capability criteria. By using those rules and Eqs. (5)–(8), the belief decision matrix *D* about the MBTs is shown as Table 8:

Step 4. Aggregating assessment by the ER approach:

In order to show how to aggregate the sub-capabilities of an upper level capability, we take *armament* capability assessment of the Leopard 2 MBT as an example. The capability assessment criteria hierarchy is depicted as Fig. 2. There are four sub-capabilities associated with *armament* capability: *main gun, coaxial gun, anti-aircraft gun*, and *Smoke Grenade Launchers.* The belief decision matrix *D* is shown as the marked area of Table 8.

$$S(main) = \{(\text{'Worst'}, 0), (\text{'Poor'}, 0), (\text{'Average'}, 1), (\text{'Good'}, 0), (\text{'Excellent'}, 0)\},$$

$$S(coaxial) = \{(\text{'Worst'}, 0.38), (\text{'Poor'}, 0.62), (\text{'Average'}, 0), (\text{'Good'}, 0), (\text{'Excellent'}, 0)\},$$

$$S(anti\_aircraft) = \{(\text{'Worst'}, 0.38), (\text{'Poor'}, 0.62), (\text{'Average'}, 0), (\text{'Good'}, 0), (\text{'Excellent'}, 0)\},$$

$$S(smoke\_grenade) = \{(\text{'Worst'}, 0), (\text{'Poor'}, 0), (\text{'Average'}, 0), (\text{'Good'}, 0), (\text{'Excellent'}, 0)\}.$$

Note that for Leopard 2 MBT, the belief degree of *smoke grenade launchers* capability is zero with respect to any evaluation grades here, which is due to the fact that there is no information about the *smoke grenade launchers* capability for it. From Fig. 2 and the expressions above, we have,

$$\beta_{1,1} = 0, \quad \beta_{2,1} = 0, \quad \beta_{3,1} = 1, \quad \beta_{4,1} = 0, \quad \beta_{5,1} = 0,$$

$$\beta_{1,2} = 0.38, \quad \beta_{2,2} = 0.62, \quad \beta_{3,2} = 0, \quad \beta_{4,2} = 0, \quad \beta_{5,2} = 0,$$

$$\beta_{1,3} = 0.38, \quad \beta_{2,3} = 0.62, \quad \beta_{3,3} = 0, \quad \beta_{4,3} = 0, \quad \beta_{5,3} = 0,$$

$$\beta_{1,4} = 0, \quad \beta_{2,4} = 0, \quad \beta_{3,4} = 0, \quad \beta_{4,4} = 0, \quad \beta_{5,4} = 0.$$

The weight vector of four sub-capability criteria is $\omega = (0.5, \quad 0.2, 0.2, 0.1)$.

According to Eqs. (9)–(12), the aggregation operational process is as follows:

$$m_{1,1} = w_1\beta_{1,1} = 0.5 \times 0 = 0, \quad m_{2,1} = 0, \quad m_{3,1} = 0.5,$$
$$m_{4,1} = 0, \quad m_{5,1} = 0, \quad \bar{m}_{H,1} = 0.5, \quad \tilde{m}_{H,1} = 0,$$

$$m_{1,2} = 0.076, \quad m_{2,2} = 0.124, \quad m_{3,2} = 0, \quad m_{4,2} = 0,$$
$$m_{5,2} = 0, \quad \bar{m}_{H,2} = 0.8, \quad \tilde{m}_{H,2} = 0,$$

$$m_{1,3} = 0.076, \quad m_{2,3} = 0.124, \quad m_{3,3} = 0, \quad m_{4,3} = 0,$$
$$m_{5,3} = 0, \quad \bar{m}_{H,3} = 0.8, \quad \tilde{m}_{H,3} = 0,$$

$$m_{1,4} = 0, \quad m_{2,4} = 0, \quad m_{3,4} = 0, \quad m_{4,4} = 0,$$
$$m_{5,4} = 0, \quad \bar{m}_{H,4} = 0.9, \quad \tilde{m}_{H,4} = 0.1.$$

From Eqs. (13)–(18), we have

$$k = \left[\sum_{n=1}^{N}\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{H,i} + \tilde{m}_{H,i}) - (N-1)\prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i})\right]^{-1} = 1.2337,$$

Table 11
Attack capability.

	Expected utilities			Rank
	Minimum	Maximum	Average	
Type 98 MBT (China)	0.6688	0.6688	0.6688	1
M1A2 Abrams (USA)	0.5320	0.5320	0.5320	2
Challenger 2E MBT (UK)	0.5079	0.4648	0.4864	3
Leopard 2 MBT (Germany)	0.5062	0.4143	0.4603	4

Table 12
Mobility capability.

	Expected utilities			Rank
	Minimum	Maximum	Average	
Type 98 MBT (China)	0.5947	0.5947	0.5947	2
M1A2 Abrams (USA)	0.4338	0.4338	0.4338	4
Challenger 2E MBT (UK)	0.5305	0.5305	0.5305	3
Leopard 2 MBT (Germany)	0.7754	0.7754	0.7754	1

Table 13
Defense capability.

	Expected utilities			Rank
	Minimum	Maximum	Average	
Type 98 MBT (China)	0.6792	0.6792	0.6792	3
M1A2 Abrams (USA)	0.8665	0.8665	0.8665	2
Challenger 2E MBT (UK)	0.9466	0.9466	0.9466	1
Leopard 2 MBT (Germany)	0.5912	0.5912	0.5912	4

Table 14
Communication & command capability.

	Expected utilities			Rank
	Minimum	Maximum	Average	
Type 98 MBT (China)	0.5000	0.5000	0.5000	4
M1A2 Abrams (USA)	0.8619	0.8619	0.8619	1
Challenger 2E MBT (UK)	0.8367	0.6088	0.7228	2
Leopard 2 MBT (Germany)	0.6143	0.4852	0.5498	3

Table 15
Overall capability.

	Expected utilities			Rank
	Minimum	Maximum	Average	
Type 98 MBT (China)	0.6265	0.6265	0.6265	3
M1A2 Abrams (USA)	0.6484	0.6484	0.6484	1
Challenger 2E MBT (UK)	0.6704	0.6227	0.6465	2
Leopard 2 MBT (Germany)	0.6166	0.5720	0.5943	4

$$m_{n=1} = k\left[\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i})\right] = 0.0786,$$

$$m_{n=2} = 0.1319, \quad m_{n=3} = 0.3948, \quad m_{n=4} = 0, \quad m_{n=5} = 0;$$

$$\bar{m}_H = k\left[\prod_{i=1}^{L}\bar{m}_{H,i}\right] = 0.3553, \quad \tilde{m}_H = k\left[\prod_{i=1}^{L}(\bar{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{L}\bar{m}_{H,i}\right] = 0.0395;$$

$$\beta_{n=1} = \frac{m_n}{1 - \bar{m}_H} = 0.1219, \quad \beta_{n=2} = 0.2045, \quad \beta_{n=3} = 0.6124,$$

$$\beta_{n=4} = 0, \quad \beta_{n=5} = 0, \quad \beta_H = \frac{\tilde{m}_H}{1 - \bar{m}_H} = 0.0612.$$

The result is $S(armament)$ = {('Worst',0.1219), ('Poor', 0.2045), ('Average',0.6124), ('Good',0), ('Excellent',0)}. The unknown (or ignorance) is 0.0612 due to the lack of information.

Similar to the above calculations, assessment results at higher level of capabilities of these four MBTs can be obtained. Table 9 gives the aggregated assessment results of the four main capabilities of the four MBTs, and Table 10 gives the overall result. (In Tables 9 and 10, assessment results are expressed as vectors. For example, the *Attack* capability of Leopard 2 MBT is (0.0837, 0.1871, 0.4431, 0.1942, 0.0000, 0.0919), which means $S(attack)$ = {('Worst',0.0837), ('Poor',0.1871), ('Average',0.4431), ('Good',0.1942), ('Excellent',0)}, the ignorance is 0.0919).

Step 5. Calculating and analyzing assessment result:

Suppose the utilities of the evaluation grades as given by experts are as follows:

$$u(\text{Worst}) = 0, \quad u(\text{Poor}) = 0.2, \quad u(\text{Average}) = 0.5,$$
$$u(\text{Good}) = 0.8, \quad u(\text{Excellent}) = 1.$$

Then the minimum, maximum and average expected utilities of each of the four main capabilities and the overall capability of the MBTs are presented in Tables. 11–15, by using the utility interval ranking method (Eqs. (20)–(23)).

In summary, from Tables 11–15, among the four MBTs considered above, Type 98 MBT (China) has the best *attack capability*; and Leopard 2 MBT (Germany) has the best *mobility capability*. In the *defense capability* aspect, Challenger 2E MBT (UK) is assessed to be the best. As to the *communication* & *command capability*, the M1A2 Abrams (USA) is the best.

The overall capability of the 4 MBTs can be ranked by their average utility as:

M1A2 Abrams (USA) $\succ$ Challenger 2E (UK) $\succ$ Type 98 (China) $\succ$ Leopard 2 (Germany).

5. Conclusion

Weapon System Capability Assessment (WSCA) problem is a strategic issue and has significant impacts to the military capability planning and development. It is considered as multiple criteria decision making problem under uncertain environment. To assess the capabilities of weapon systems, information of different nature such as quantitative, qualitative, linguistic, vague, and incomplete information about a weapon system must be taken into account. The belief structure concept provides a uniform framework and an effective method to deal with the problem. Rationally aggregating of capability information with uncertainty is also considered as a key issue in the analysis process. This study presents and illustrates a scientific framework to assess weapon system capability using the evidential reasoning approach.

In the study and analysis, the steps for WSCA is proposed. Using the proposed assessment analysis process, a real Main Battle Tank (MBT) capability assessment problem is explored. Through the assessment and comparison of four MBTs, we have illustrated how to rank the MBTs by combining the preferences of decision makes (through weights and utilities) with the capability performances of each MBT. We have built the capability assessment criteria hierarchy for WSCA, transformed different types of information into a unified BS, and aggregated the performance information of the MBTs using the ER algorithm.

Assessment of weapon systems is an important aspect of military capability planning and development. The proposed analysis approach for WSCA provides a rational way to assess and analyze the capabilities of large and complex weapon systems under uncertainties.

Acknowledgments

The author is indebted to the anonymous reviewers for their accurate comments and suggestions that helped improve the work presented in this paper. This paper is supported by National Natural Science Foundation of China. Nos. 70971131, 70901074, and 61004069.

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